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Cold inertance tube for 4 K Stirling type pulse tube cryocoolers

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Abstract

The losses in the regenerator are minimized when the amplitude of the mass flow is minimized for a given acoustic power which requires that the mass flow lags the pressure by about 30° at the cold end of regenerator. The phase shift provided by an inertance tube is strongly influenced by the temperature of the inertance tube and the acoustic power at the cold end of the regenerator. For a 4 K Stirling type pulse tube cryocooler, the acoustic power at the cold end of the regenerator decreases significantly with the temperature thereby it's difficult to achieve ideal phase relationship with ambient inertance tube. While cold inertance tube provide a larger phase shift in that the viscosity of the working fluid decreases and the density increases as the temperature decreases. However, use of cold inertance tube increases additional heat load to the regenerator. Therefore it's of great significance to determine when a cold inertance tube should be used. In this paper effect of temperature of inertance tube is calculated for a 4 K Stirling type pulse tube cryocooler with different acoustic powers at the cold end. A comparison of ambient temperature inertance tube and cold inertance tube is made.

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Keywords: cold inertance tube; 4 K; regenerator; Stirling; pulse tube cryocooler

1. Introduction

Pulse tube cryocoolers (PTC) use phase shifter to adjust the mass flow and the pressure to the ideal phase angle to decrease the regenerator losses. The regenerator losses are minimized when the mass flow and the pressure are in

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phase in the middle of the regenerator which leads to minimum amplitude of the mass flow [Radebaugh et al. (2006)].The inertia of a narrow and elongated inertance tube functions as the gas equivalent of an inductor which makes the mass flow to lag the pressure to the optimum value.The amplitude of the mass flow in the regenerator is reduced due to the phase relationship and the efficiency of regenerator is improved. The phase shift provided by the inertance tube is strong function of temperature in that the properties of the helium such as density and viscosity changes significantly with the temperature [Jeffrey and Olson (2005)]. As the temperature decreases, the density of helium increases and the viscosity decreases leading to a larger inertia effect [Gan et al. (2009)]. For a 4 K Stirling type pulse tube cryocooler (SPTC), the acoustic power (pV power) at the cold end decreases with the temperature as a result of the reduced specific volume. It's difficult to achieve enough phase shift with small acoustic power with ambient inertance tube. Use of cold inertance tube helps achieve larger phase angle and reduces regenerator losses. However, it will lead to additional heat load to the regenerator. Therefore it's of great significance to determine when a cold inertance tube should be used. In this paper effect of temperature of inertance tube is calculated for a 4 K Stirling type pulse tube cryocooler with different acoustic powers at the cold end. A comparison of ambient temperature inertance tube and cold inertance tube is made and the results are presented.

2. Numerical calculation model

As the pressure amplitude decreases along the length of the inertance tube the enthalpy flow decreases leading to heat dissipation along the inertance tube. The advantage of placing the inertance tube at ambient temperature is that the heat can be removed directly to the ambient environment. For the case of cold inertance tube, the inertance tube has to be placed adjacent to a cold sink (typically some part of the regenerator) and the heat is transferred to the regenerator causing additional heat load to the overall system. A numerical calculation model was set up by using a single-stage SPTC precooled by a two-stage SPTC to investigate the effect of temperature on the performance of the 4 K SPTC with different acoustic power at the entrance to the inertance tube (warm end of the pulse tube) based on REGEN 3.3 [Gary et al (2006), Huang et al (2006)]. The model is based on the equations of conservation of mass, momentum and energy and the accuracy of REGEN has been verified experimentally [Vanapalli et al (2007), Gan et al (2008)].

The regenerator efficiency is only influenced by the velocity (mass flow at the cold end (m_c) divided by void volume of helium (A_g) of helium in the regenerator with some given operating parameters (such as frequency, average pressure and pressure ratio at the cold end). The 4 K SPTC is scaled up with a fixed ideal value (m_c /A_g equals 3.3 g/s-cm^2) based on previous calculation. The value of Ag and mc is magnified simultaneously with the fixed ratio. In this paper, performance of a 4 K SPTC with acoustic power at the cold end of 0.1, 0.5, 1.0 and 5 W is calculated with an inertance tube being placed at 300, 80 and 10K as shown in Fig. 1.

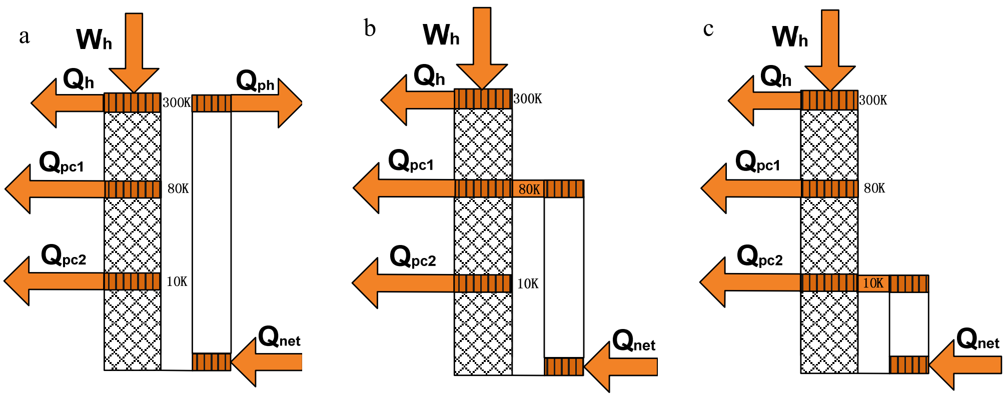

Fig. 1. A precooled single-stage 4 K SPTC with inertance tube at different temperatures (a) 300 K inertance tube; (b) 80 K inertance tube; (c) 10 K inertance tube.

The main parameters used in the numerical calculation or the 4 K SPTC with inertance tube at different temperatures are listed in Table 1. The operating frequency is 30 Hz, the average pressure is 1.0 MPa and the pressure ratio at the cold end is 1.2. For the details of the regenerator please see [Li et al (2014)]. The phase angle between the mass flow and the pressure is determined by calculating the maximum phase shift of inertance tube with different diameters and lengths at different temperatures [Chen et al (2009)]. A phase angle of -30° with the mass flow lags the pressure is chosen as the phase angle at the cold end of the pulse tube.

Table 1. Main parameters used in the numerical calculation for the 4K SPTC with inertance tube.

regenerator	Tc（K）	Th（K）	0.1 W		0.5 W		1 W		5 W		L (mm)
			Ag (cm^2)	mc (g/s)	Ag (cm^2)	mc (g/s)	Ag (cm^2)	mc (g/s)	Ag (cm^2)	mc (g/s)	
I	80	300	0.37108	-	1.8554	-	3.7108	-	18.554	-	30
II	10	80	0.37108	-	1.8554	-	3.7108	-	18.554	-	25
III	4	10	0.22998	0.3	1.1499	1.5	2.2998	3	11.499	15	30

3. Calculation results

3.1. *Effect of temperature of the inertance tube on the cooling power and input acoustic power*

Fig. 2(A) and (B) give the effect of temperature of the inertance tube on the cooling power and acoustic power at the hot end of the regenerator. As can be seen from Fig. 2(A), no cooling power is obtained when the inertance tube is placed at 80 and 300 K due to the small phase shift. For the case with 10 K cold inertance tube, a cooling power is 1.79 mW. The cooling power is increased with an ambient inertance tube when the acoustic power at the cold end is increased to 5 W. Fig. 2(B) shows that the acoustic power at the hot end of the regenerator increases with the temperature of the inertance tube.

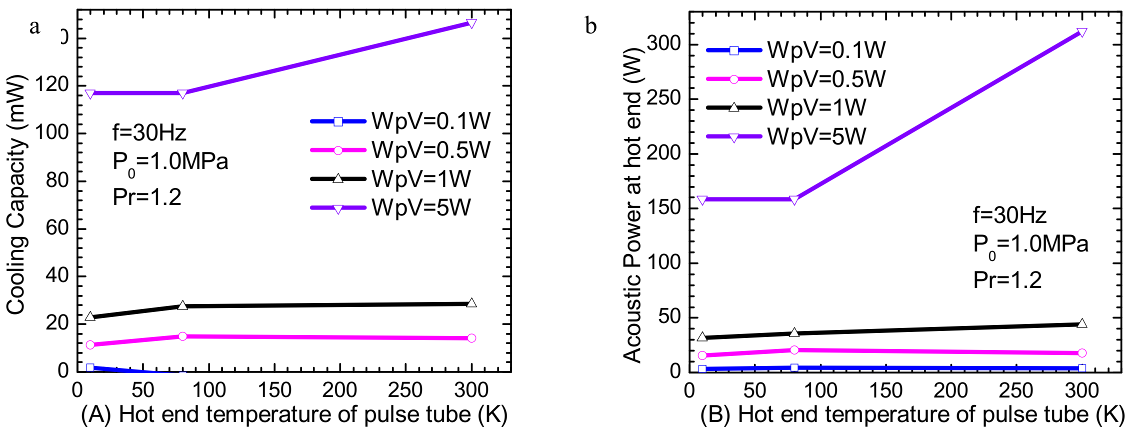

Fig. 2. Effect of temperature of inertance tube on (A) cooling power and (B) input acoustic power.

3.2. *Effect of temperature of the inertance tube on the precooling power*

Fig. 3(A) and (B) give the effect of temperature of inertance tube on the first and second precooling power provided by the precooler. The fisrt precooling power is largest for the case of 80 K cold inertance tube due to the fact that the enthalpy flow in the pulse tube has to be dissipated to the cold end of the first stage of the precooler. When the temperature of the inertance tube is decreased to 10 K, the regenerator losses are reduced due to the improved phase relationship between the mass flow and the pressure. However, the second precooling power is increased for there is additional heat load caused by the enthalpy flow in the pulse tube. Larger acoustic power at the cold end adds more heat load to the precooler and the efficiency of the system is reduced.

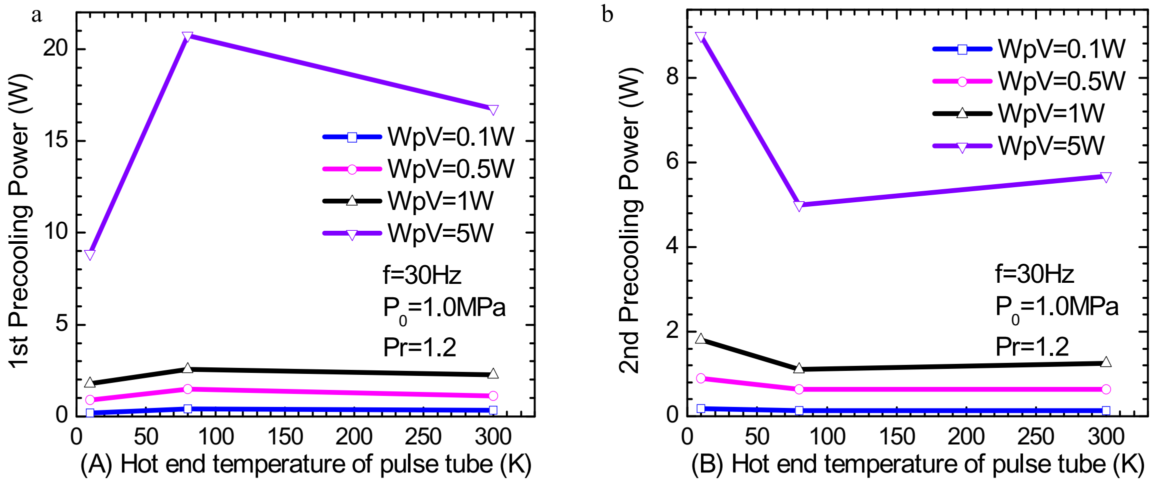

Fig. 3. Effect of temperature of inertance tube on (A) first precooling power and (B) second precooling power.

3.3. Effect of temperature of the efficiency of the system

In order to evaluate the efficiency of the whole system with precooling, the precooling power is transformed to the input power of the compressor according to the typical specific power (input power of compressor divided by cooling power) at the corresponding temperature regions.

The data of the typical specific power is obtained based on the review of small-scale cryocooler made by Ter Brake in 2002 [Ter Brake et al. (2002)]. According to the reference, the specific power of 80 and 10K of a cryocooler is about 0.05 and 2 kW/W.

Fig. 4 compares the specific power of the SPTC with inertance tube at 10, 80 and 300 K. Therefore the COP of the 4 K SPTC with precooling can be expressed as:

$$COP = \frac{Q_{net}}{W_{tot}} = \frac{Q_{net}}{W_{precooling1} + W_{precooling1} + W_{sptc}} = \frac{Q_{net}}{50 \times Q_{precooling1} + 2000 \times Q_{precooling1} + W_{sptc}}, \tag{1}$$

where Q_{net} is the net cooling power of the 4 K SPTC, W_{tot} is the total input power of the compressor of the 4 K SPTC with precooling, $W_{precooling1}$ is the input power of the compressor of the first stage of the precoler (refrigaration temperature is 80 K), $W_{precooling2}$ is the input power of the compressor of the second stage of the precoler (refrigaration temperature is 10 K), W_{sptc} is the input power of the compressor of the single-stage 4K SPTC. The specific power of the system $P_{specific}$ equals to 1/COP.

The influence of temperature of inertance tube on the specific power of the 4 K SPTC with different acoustic power at the cold end is given in Fig. 4. When the acoustic power at the cold end is 0.1 W, no cooling power is obtained with 80 and 300 K inertance tube.

The specific power is minimum when the inertance tube is placed at 80 K with the acoustic power of 0.5 and 1 W. Even though the enthalpy of the pulse tube at the hot end becomes additional heat load to the first stage precooler, the phase relationship between the mass flow and pressure is improved leading to reduced regenerator losses. Therefore the efficiency of the whole system is increased.

While for the case of 5 W acoustic power, use of ambient inertance tube at 300 K yields the highest efficiency because the phase shift provided by 300 K inertance tube is enough to provide ideal phase relationship without additional heat load to the precooler.

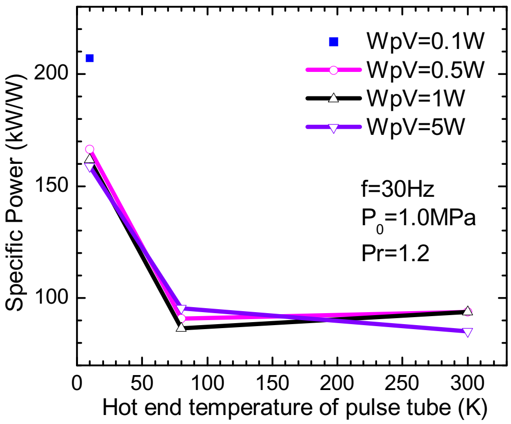

Fig. 4. Effect of temperature of inertance tube on specific power of 4 K SPTC with precooling.

4. Conclusion

Based on a single-stage 4 K SPTC precooled by a two-stage cryocooler, influence of temperature of inertance tube is investigated with different acoustic powers at the cold end. The efficiency of the whole system with the precooler is evaluated by transforming the precooling power into the compressor input power of according to typical specific power of cryocoolers. Efficiency of the 4 K SPTC is improved by use of cold inertance tube when the acoustic power at the cold end is as small as about 0.1 W. While for a system with a acoustic power at the cold end as large as about 5 W, ambient inertance tube is better choice.

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